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# Contribution of old wheat varieties to climate change mitigation under contrasting managements and rainfed Mediterranean conditions

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A B S T R A C T

Agriculture represents about 11% of global anthropogenic greenhouse gas emissions (GHGe). Many climate change mitigation strategies have been evaluated in Mediterranean agroecosystems, including their soil organic carbon sequestration potential. High residue yielding old varieties could constitute a useful alternative, especially for organic farming, which lacks specific genetic material. In this study, old and modern wheat varieties were evaluated under organic (ORG) and conventional (CON) management during a 3-year field experiment under rainfed Mediterranean conditions. Field measurements of biomass components, literature emission factors, and soil organic carbon modeling were combined in an attributional Life Cycle Assessment, in order to estimate GHGe from "cradle to farm gate". The resulting yield-based carbon footprints of old wheat varieties were significantly lower than those of modern varieties both under CON management, decreasing from 263 to 144 g $CO_2e$ $kg^{-1}$, and under ORG management, decreasing from 29 to −43 g $CO_2e$ $kg^{-1}$. Our results indicate that climate change mitigation strategies in Mediterranean rainfed cereal cropping systems should focus on diminishing GHGe from machinery and fertilizer use, and promoting carbon sequestration. The combination of organic management and old cereal varieties can constitute a promising climate change mitigation strategy in these systems, as low area-scaled GHGe of organic management are combined with enhanced carbon sequestration and a good yield performance of old varieties under these conditions.



## 1. Introduction

The agricultural sector represents about 11.2% of global anthropogenic greenhouse gas emissions (GHGe) in 2010 or up to 21.2% when including land use changes (Tubiello et al., 2015). Mediterranean cropping systems have specific pedoclimatic conditions that affect their GHGe pattern, conditioning the effectiveness of climate change mitigation strategies and their wider environmental impacts (Sanz-Cobena et al., 2017). Rainfed Mediterranean cereal fields are expanding, and their importance for Mediterranean agriculture sustainability is increasingly acknowledged (Perniola et al., 2015). For example, Tahmasebi et al. (2018) recently found that rainfed Mediterranean wheat cropping systems are more sustainable than irrigated ones due to a lower input intensity. They concluded that the higher yield of irrigated systems did not compensate for the unproportioned increase in GHGe. The major contributor to GHGe in Mediterranean rainfed cereal cropping systems is the use of industrial inputs, such as machinery and fuel for organic farms and these together with fertilizer in conventional ones (Aguilera et al., 2015a). For instance, Ali et al. (2017) found that the production and application of N fertilizer represented up to 60% of the C footprint of rainfed wheat in Italy. Many practices have been evaluated for their climate change mitigation potential, including conservation tillage (Álvaro-Fuentes et al., 2007), biochar application (Castaldi et al., 2011), or the use of organic fertilizers (Meijide et al., 2010). In addition, the inclusion of legumes in rotations can reduce GHGe through lowering N fertilizer inputs (Liu et al., 2016).

Soil organic carbon (SOC) is key for climate change adaptation

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and mitigation processes in agricultural systems (Lal, 2004). Changes in SOC have been widely studied in cereal fields (Blanco-Moure et al., 2016), and under Mediterranean conditions (Aguilera et al., 2013), and specifically in Mediterranean rainfed cereal systems (e.g. Guardia et al., 2016). SOC increases can offset an important proportion of agricultural GHGe (Parton et al., 2015), thus not including SOC sequestration in the GHGe accountability can lead to underestimations of the GHGe abatement potential of agriculture (Rodríguez-Entrena et al., 2014).

Concerns about climate change have led to many studies discussing the C storage potential of organic material additions to agricultural soils (Lehtinen et al., 2014). Typically, SOC increases in proportion to increases in C inputs (Paustian et al., 2000), and this is also true for Mediterranean systems (Aguilera et al., 2013). In Mediterranean areas (Aguilera et al., 2013), and particularly in Spain (Rodríguez-Martín et al., 2016), cropland soils have low SOC concentrations. Mediterranean cropland soils are far from their potential for SOC storage (Aguilera et al., 2013), and SOC depletion is a major vulnerability factor for the sustainability of Mediterranean agriculture in a climate change context (Iglesias et al., 2011).

Organic farming can offer valuable environmental benefits (Tuomisto et al., 2012), including those regarding climate change mitigation and adaptation (Scialabba and Muller-Lindenlauf, 2010). In Mediterranean cereal systems, organic farming has been found to lower GHGe per unit area (Gutiérrez et al., 2017), but not always per unit product. Aguilera et al. (2015a) found lower C footprint per unit of product for organic systems, while Fedele et al. (2014) found the opposite when comparing with conventional farming. Likewise, organic farming can increase SOC (Aguilera et al., 2013) as compared to conventional management. Unfortunatelly, there is no specific genetic material for organic farming, so it relies on varieties selected under conventional high-input agriculture conditions (Murphy et al., 2007). There is a need for selecting varieties better adapted to organic farming and low input conditions (Murphy et al., 2007) and some authors have proposed old varieties as a valuable source for sustainable agriculture in a climate change context (Bellucci et al., 2013), more suitable to adapt to future scenarios (Ceccarelli and Grando, 2000). Wheat varieties experienced an unprecedented harvest index increase throughout the past century (Smil, 1999) leading to a great increase in grain yield without a significant change in total aboveground biomass (De Vita et al., 2007). However, a future decrease in harvest index under Mediterranean conditions has been modelled (Moriondo et al., 2011), mainly due to heat stress caused by climate change. In this context, growing varieties with high residue production can result in an effective climate change mitigation strategy.

Our hypothesis is that old wheat varieties cultivation, specially under organic management, can contribute to decrease the C footprint of rainfed Mediterranean cereal cultivation through a higher production of residues. In this study, we evaluated the C footprint of rainfed Mediterranean cereal production as affected by varieties (old versus modern) and managements (organic versus conventional). We carried out a field experiment in Southern Iberian Peninsula to estimate the C footprint of old and modern wheat varieties under organic and conventionall farming practices. The 3-years field data were processed in a life cycle assessment (LCA) to calculate the full GHG balance of the cropping systems and their products, including C sequestration.

## 2. Material and methods

### 2.1. Site description and experimental design

Two field experiments under different management were carried out at two locations 142 km away in Southern Iberian Peninsula (Figure S1), Sierra de Yeguas (Málaga province) and La Zubia (Granada province). To cover for interannual variability, the field experiments were carried out during three consecutive growing seasons (2013–2016). The main soil properties of the experimental sites are shown in Table 1. Temperature and precipitation data are shown in Table 2. Mean annual temperature for the experiment locations during the study period are close to their corresponding mean values for the last 30 years. However, annual precipitation was 56.4% and 68.9% of the mean value, for Sierra de Yeguas and La Zubia, respectively. The same old (OV, *Rubio, Recio, Sierra Nevada, Barbilla Roja, Rojo Pelón, Blanco Verdial*) and modern (MV, *Avispa, Simeto, Vitrón, García, Marius, Artur Nick*) wheat varieties were sown at both locations. OV were landraces grown during the first third of the 20th century in the region. Their seeds came from the Phytogenetic Resource Centre of the National Agrarian Research Institute of Spain (CRF-INIA). MV were chosen among lately released, currently used varieties, considering their good reputation among farmers in the area.

The farmland at Sierra de Yeguas had been under organic management (ORG) (Table 2) for the previous 15 years. Crop rotation consisted of wheat-legume (*Vicia faba*). Both species were grown in adjacent plots, interchanging cultivation plots each year. Before wheat seeding in the first year of the rotation, 3 Mg ha$^{-1}$ of poultry manure was applied, but none to faba bean crop. Poultry manure mineralization was assumed as two thirds and one third for the first and second year of the rotation scheme, respectively. Weeds were controlled by hand. The farmland at La Zubia was conventionally managed (CON), based on monoculture wheat cropping and synthetic inputs. Complex synthetic fertilizer was applied before seeding (Table 2) and a broad-leaf herbicide was applied before stem elongation. At both farms, wheat was usually grown before the field experiment. Although we do not have available data from previous years, farmers from both locations identified yield levels within typical ranges in the region drylands.

Both fields were planted between October 25 and November 12. Sowing rate was 200 kg ha$^{-1}$ for wheat and 110 kg ha$^{-1}$ for faba bean. Harvest took place between June 5 and June 25. Wheat and faba bean were seeded and harvested at the same time. Each trial consisted of a complete randomized block design with four blocks separated with a non-seeded stripe 1 m width. Plots were 6 × 4 m$^2$ size.

**Table 1**
Soil physico-chemical properties of the field trials at the beginning of the experiment. Mean values and standard error are shown.

| Properties | Sierra de Yeguas | La Zubia |
|---|---|---|
| CEC (meq/100 g) | 31.2 ± 0.93 | 16.9 ± 0.85 |
| Ca exchangeable (meq/100 g) | 21.9 ± 0.79 | 13.8 ± 0.93 |
| Mg exchangeable (meq/100 g) | 5.80 ± 0.54 | 2.05 ± 0.72 |
| Na exchangeable (meq/100 g) | 1.34 ± 0.07 | 0.50 ± 0.07 |
| K exchangeable (meq/100 g) | 2.12 ± 0.05 | 0.48 ± 0.02 |
| Carbonate (%) | 12.3 ± 3.17 | 18.6 ± 0.20 |
| Limestone (%) | 4.61 ± 1.71 | 4.71 ± 0.43 |
| Olsen P (ppm) | 33.7 ± 4.44 | 27.0 ± 6.55 |
| SOC (%) | 1.39 ± 0.11 | 1.51 ± 0.17 |
| N org (%) | 0.16 ± 0.01 | 0.17 ± 0.01 |
| pH | 8.18 ± 0.02 | 7.99 ± 0.05 |
| pH in ClK | 7.46 ± 0.02 | 7.46 ± 0.03 |
| Assimilable K (ppm) | 927.0 ± 27.25 | 208.4 ± 6.23 |
| Clay (%) | 42.2 ± 1.14 | 16.4 ± 1.17 |
| Sand (%) | 18.6 ± 1.40 | 28.7 ± 3.52 |
| Silt (%) | 39.1 ± 0.85 | 54.8 ± 2.40 |
| Texture | Clay | Silt-loam |

CEC = cation exchange capacity; SOC = soil organic carbon.

**Table 2**
Annual temperature and rainfall and management practices of the field experiments.

| Location | ORG | CON |
|---|---|---|
| | Sierra de Yeguas | La Zubia |
| Mean temperature (°C) | | |
| 2013–2014 | 16.0 | 15.3 |
| 2014–2015 | 16.6 | 17.0 |
| 2015–2016 | 16.9 | 15.4 |
| 1982–2012 average | 16.3 | 15.2 |
| Rainfall (mm) | | |
| 2013–2014 | 433 | 309 |
| 2014–2015 | 344 | 359 |
| 2015–2016 | 363 | 288 |
| 1982–2012 average | 673 | 462 |
| Farming system | Organic | Conventional |
| Rotation | Wheat-Faba bean | Monoculture |
| Fertilization | Poultry manure | NPK |
| | (3.6% N, d.m.) (3.0 Mg $ha^{-1}$, f.m.) | (8:15:15) (570 kg $ha^{-1}$) |
| N (kg $ha^{-1}$) | 54 (wheat) + 27 (faba bean) | 45.6 |
| P (kg $ha^{-1}$) | n.d. | 85.5 |
| K (kg $ha^{-1}$) | n.d. | 85.5 |
| Weed control | Manual weeding | MCPA 40% (2 l $ha^{-1}$) |
| Irrigation | Rainfed | Rainfed |

f.m. and d.m. stands for fresh and dry matter respectively, whereas n.d. means not determined.
MCPA = 2-methyl-4-chlorophenoxyacetic acid, active ingredient of applied herbicide.

### 2.2. Sampling methods

Grain yield, aboveground wheat and weed biomass were measured by harvesting two 0.5 × 0.5 $m^2$ squares at each subplot that were previously randomly thrown at the centre of the subplot. Wheat and weed biomass were dried at 70 °C to obtain dry weight. Fresh spikes were threshed to separate grain and grain husk before they were dried in the oven. Data for OV and MV were the average for the six old and six modern varieties, respectively.

Root biomass was sampled at anthesis for cultivars planted at the ORG trial, at the third year of the experiment. Two soil cubes of 25 × 25 × 25 $cm^3$ were extracted at the centre of each plot, washed and sieved (2 mm) at farm-gate. At the laboratory, root biomass was washed, extracted and estimated following Metcalfe et al. (2007). The extrapolated value of root biomass, on the basis of the logarithmic equation obtained through this method, increased by 20% and 17% the extracted root biomass of OV and MV, respectively. For CON root biomass, it was assumed the same absolute data obtained for ORG.

### 2.3. C and N determinations

Dried samples of grain, straw, husk, weed and root biomass were milled (<1 mm) and analysed for C and N content with an elemental autoanalyser CNOH-S (Flash EA1112 CHNS-O, Thermo Finnigan).

### 2.4. LCA analysis

#### 2.4.1. Goals and scope

The goal was to compare the C footprint of old and modern wheat varieties under ORG and CON managements and Mediterranean climate conditions. For this purpose, a global warming impact assessment was performed following the standards of ISO (2006) guidelines for LCA methodology. Our major aim was to identify if the cultivation of high residue producing varieties (OV) could constitute an advantage to climate change mitigation strategies, taking into account their potential benefits for soil carbon sequestration. An additional goal was to highlight the hotspots in the GHG profile of these systems, helping to focus efforts for reducing their C footprint. The temporal boundaries were adjusted to 100 years by selecting the 100-year GWP of nitrous oxide ($N_2O$) and employing a 100-year averaged C sequestration rate. The system boundaries were stablished from a “cradle to farm gate” approach, including the production of farming inputs and machinery, on-farm operations and off-farm emissions due to N losses from the agroecosystem. We chose 1 ha of land and 1 kg of product as functional units. An attributional life cycle assessment was also applied, and allocation of emissions to production followed an economic criterion, based on market prices of products and co-products. For ORG trial, both crops products (wheat and faba bean grains) were accounted for, while only wheat straw was considered as co-product.

#### 2.4.2. Inventory analysis

Based on “the cradle to farm gate” approach, we considered inputs and outputs for the production of one kg of wheat per hectare from the inputs production phase to the emissions derived from N losses from the field (Fig. 1). The pre-farm step covered the emissions from production of inputs: seeds, fertilizer, machinery and fuel. The on-farm step included two sources of emissions. On the one hand, emissions derived from the use of machinery for field labors. On the other hand, the emissions derived from the N applied to soil in form of chemical and organic fertilizer and crop residues. The off-farm emissions were indirect emissions due to ammonia ($NH_3$) volatilization and nitrate ($NO_3^-$) lixiviation processes.

#### 2.4.3. Impact assessment

Total GHGe were the results of calculating emissions from inputs production and on-farm activities and direct and indirect $N_2O$ emissions from chemical/organic fertilizer application and crop residues incorporation to soil. Emissions from $N_2$ fixation by the legume were not considered (Barton et al., 2011). $N_2O$ emissions were transformed to kg $CO_2$eq with a GWP of 265 (IPCC, 2014). The final C footprints were calculated as the total GHGe minus the $CO_2$eq related to C sequestration.

*2.4.3.1. Emissions from inputs production.* GHGe from industrial inputs production were calculated from energy consumption data of Aguilera et al. (2015b). This database includes all life cycle

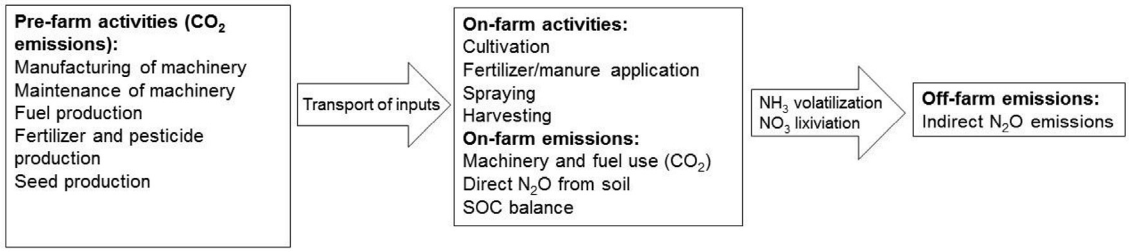


**Fig. 1.** Life Cycle Inventory and system boundaries of wheat production from inputs manufacture to wheat harvest considered in this study.

processes related to agricultural inputs production from the extraction of raw materials to the transport of commercial inputs to the farm. We applied a conversion factor of 62.8 kg $CO_2e$ $GJ^{-1}$, based on the energy mix data of 2010 (Koppelaar, 2012) and emissions factors of each type of energy from IPCC (2006). Total machinery GHGe was the sum of emissions from fuel production, and the emissions from machinery and implements manufacture and maintenance. Emission factors for industrial inputs are detailed in Table S1. Final GHGe from machinery and fuel production was expressed as kg $CO_2e$ $ha^{-1}$ emitted during each machinery task (cultivation, harvesting, fertilizer application, spraying).

*2.4.3.2. On-farm emissions.* On-farm emissions include direct emissions from fuel combustion and direct $N_2O$ emissions from soil. On-farm emissions from fuel combustion were calculated based on fuel consumption. Fuel energy consumption data for each task from Aguilera et al. (2015b) was converted to GHGe using IPCC (2006) direct fuel emission factors for farm machinery. On-farm operations were calculated from machinery and fuel production emissions and on-farm fuel use emissions. Data from previous section were multiplied by the number of tasks needed for each labor.

Following IPCC (2006), direct $N_2O$ emissions from the soil were calculated based on N applications, including organic and chemical fertilizer and crop/weed residues (aboveground and belowground) incorporated to the soil. Total N (kg $ha^{-1}$) from these inputs was multiplied by a specific emission factor (EF) for Mediterranean rainfed systems (0.27% of N inputs) (Cayuela et al., 2017) to calculate direct $N_2O$-N emissions.

*2.4.3.3. Indirect $N_2O$ emissions.* Indirect emissions were calculated from soil $NO_3^-$ leaching and $NH_3$ volatilization following IPCC (2006) schedule. N loss by $NO_3^-$ leaching was assumed to be zero. This assumption was based on the fact that annual evapotranspiration was 3.4 times higher than annual rainfall (data not shown). Only from January to February 2013 and in November 2014, monthly rainfall was greater than evapotranspiration, but soil water accumulation never exceeded soil water holding capacity. N loss as $NH_3$ volatilization was estimated as a 2.5% and 17% of the N applied for synthetic and organic fertilizer, respectively (EEA, 2007). Indirect emissions due to $NH_3$ volatilization were calculated only for poultry and chemical fertilizer. N losses were transformed into $N_2O$ emissions using IPCC (2006) indirect $N_2O$ EFs for $NO_3^-$ leaching and $NH_3$ volatilization.

*2.4.3.4. Soil carbon balance.* SOC balance entails negative emissions when C from the atmosphere is sequestered, and positive when C is emitted to the atmosphere. To estimate SOC balance, we applied the dynamic SOC model *Humified Soil Organic Carbon* (HSOC) model (Aguilera et al., 2018), which is a simplified version of RothC model (Coleman and Jenkinson, 2014) that has been successfully applied to Mediterranean cropping systems. HSOC is a dynamic SOC model, in which the amount of decomposed C depends on that year's stock, which changes over time. Thus, when a new management that promotes SOC accumulation is implemented, C sequestration rate is maximum the first year and decreases over the time, as SOC stock asymptotically approaches to the new equilibrium. HSOC has one inert SOC pool (IOM), and two active pools (FOM and HUM). Decomposition rates for HUM and FOM C pools were calculated using the modifying factors of Coleman and Jenkinson (2014). At Sierra de Yeguas, the resulting rates were 0.98% and 23.48% for fast and long-turnover compartment, respectively. At La Zubia trial, these rates were 0.91% and 21.92%, respectively.

The inputs to *HUM* are calculated from annual soil C inputs using humification coefficients ($H_i$), which are the result of multiplying $h_i$ (basal humification coefficients, specific for each C input type, $i$) by a soil texture modifying factor (d), specific for each soil texture. For belowground C inputs, we considered an increment of 65% of root C due to extra-root C from rhizodeposition and root turnover (Bolinder et al., 2007). $h_i$ of aboveground residues, roots, extra-root C and manure were 11.5%, 21.8%, 8% and 25.4%, respectively (Aguilera et al., 2018), and the soil texture modifying factors $d$ were 1.10 and 0.92 for Sierra de Yeguas and La Zubia, respectively. Inputs to *FOM* are calculated as the total C inputs applied to the soil minus the humified inputs. IOM is calculated following Falloon et al. (1998) equation, which we applied to the measured SOC levels of the studied soils.

Following usual management practices from the area, it was assumed that 80% of MV straw is harvested for out farm uses and 20% is incorporated to the soil. For OV, harvested straw was assumed to correspond to the absolute value of harvested straw in MV. The aim of this assumption was to emphasise the potential for C sequestration of OV against MV, due to the higher straw yield of the former. Assumption of incorporated biomass of weeds growing in wheat plots followed the same rule. In the case of faba bean, 100% of crop residue and weeds were recycled into the soil, following the typical practice in the area.

SOC changes in the ORG rotation are the result of both faba bean and wheat. However, the effects of the two crops on SOC are considered separately in this study, as well as the other components of the GHGe balance, which avoids the attribution of faba bean impacts to wheat.

### 2.5. Statistical analysis

A complete randomized block variance analysis of field-measured variables, C and N inputs and C footprints was carried out within each growing season at a significance level of 0.05. Treatment means were compared using Tukey's test at 0.05 probability level. Shapiro-Wilk's normality test was run previously to check for normal distribution. Statistix software (Analytical Software, Version 10) was used for all statistical tests.

Comparisons between ORG and CON were not carried out due to the fact that they would not only be influenced by management but also by site characteristics (e.g. soil properties, water balances, etc.).

## 3. Results and discussion

### 3.1. Grain yield, straw and weed production

OV had a significantly higher grain production than MV under ORG management in 2014, while the opposite was true in 2015 and no significant differences were found in 2016 (Table 3). Under CON management, grain yield of MV was only significantly higher than that of OV in 2014. There were not significant differences between varieties under ORG or CON management across years. The fact that MV did not significantly outyield OV under ORG management was likely due to having been bred under high nutrient availability conditions, which can make them dependent on an easy access to nutrients (Foulkes et al., 1998). Under relatively slow nutrient release typical of manure application, MV could not yield more than old cultivars, as happened in 2014 and 2016. Murphy et al. (2008) found lower mean yields for old varieties under organic fertilization, but when comparing individually, some landraces outyielded modern cultivars. On the other hand, there is a wide consensus on the better yield performance of modern cultivars under high soil nutrient availability of CON management (e.g. Fang et al., 2011), but our results did not show this pattern. This could be due to the low rainfall in the study years (Table 2), as water availability is a major factor affecting grain yield (Ayadi et al., 2016). This factor could also contribute to the absence of differences under ORG. Ferrante et al. (2017) also found that under stressful conditions (0–2.5 Mg ha$^{-1}$), there were no significant differences between cultivars of different year of release under Mediterranean conditions. Overall, grain production of OV proved to be more stable than that of MV, for both managements. Previously, less stable yields of modern cultivars across environments have been reported (Acreche et al., 2008), although the opposite has been also found (Slafer and Kernich, 1996).

Across the three growing seasons, straw production of OV was 40% and 18% significantly higher than that of MV under ORG and CON managements, respectively (Table 3). These results are in line with those of other authors (Townsend et al., 2017). In the past, relative high straw production, such of those of the OV tested in this study, was a desirable wheat trait because straw was valuable for livestock feeding and bedding. Currently, the search for soil C sequestration without compromising grain yields have made straw production desirable again (Lorenz et al., 2010), and therefore cultivation of OV, specially under ORG management, is a promising strategy for C sequestration.

Finally, weed biomass under ORG management was between 90% and 63% lower for OV than for MV. Under CON management, OV plots produced 54% lower weed biomass than MV plots. This indicates that OV showed higher competitiveness against weed. Previously, authors have pointed out that wheat varieties released before herbicide expansion are more competitive against weeds (e.g. Murphy et al., 2008). In this study, higher weed production led to higher final coproduct (data not shown) of MV.

### 3.2. Carbon inputs to the soil

Wheat aboveground C inputs ranged between 1.2 Mg ha$^{-1}$ for MV under CON management and 1.5 Mg ha$^{-1}$ for OV under ORG (Table S5), values around those found by Álvaro-Fuentes et al. (2009) for continuous barley. Crop root residues applied to the soil contributed with 1.3 Mg ha$^{-1}$ C and 0.8 Mg ha$^{-1}$ C for OV and MV, respectively (for both ORG and CON, see Section 2.2), and these values were higher than those found by Novara et al. (2016) from a wheat monoculture. The belowground C input to aboveground C input ratio for wheat is of the same order of the global revision by Mathew et al. (2017). Total C allocated belowground represented 50% of total C inputs, indicating its relevance for SOC balance accountings. The highest values for total belowground C input of MV under CON management (2.2 Mg ha$^{-1}$) were due to higher weed root C input, accordingly to higher weed biomass (Table 3). In this sense, the share of weed C contribution to the total C inputs oscillated between 62% of MV under ORG, to 18% of OV under CON. This highlights the need to include weeds in C balance studies. Indeed, the key role of weeds as a source of OC input to the soil has also been reported for Spanish cropland throughout the 20th century (Aguilera et al., 2018), and in a 50-year simulation study in a Mediterranean rainfed cereal system (De Sanctis et al., 2012).

Overall for the three growing seasons, total C inputs of OV were 32% and 27% significantly higher than those of MV under ORG and CON, respectively (Fig. 2d), mainly due to the higher straw production and roots C inputs. Regarding the legume-wheat rotation, 3-year averaged values for wheat C inputs were higher than those from faba bean (Fig. 2d).

### 3.3. Nitrogen inputs to the soil

Wheat AG residues N inputs ranged from 42.5 kg ha$^{-1}$ of OV under CON to 12.3 kg ha$^{-1}$ of MV under ORG (Table S5). Values for OV under ORG and MV under CON were similar to the 21.1 kg N ha$^{-1}$ measured in a conventionally tilled barley field (Plaza-Bonilla et al., 2014) under similar rainfed Mediterranean conditions. Crop roots N inputs reached maximums of 18 kg N ha$^{-1}$ for OV under CON and minimums of 9 kg ha$^{-1}$ for MV under ORG, and averaged values ranged those found by Plaza-Bonilla et al. (2014). Although OV root N inputs were higher than that of MV for both managements, higher weed root N inputs of MV counteracted that trend, and total belowground N inputs ranged from 29 kg N ha$^{-1}$ of OV under ORG to 41 kg N ha$^{-1}$ of MV under CON. Across years, total N inputs of OV were 8% higher than those of MV under CON

**Table 3**
Grain yield, straw biomass and weed biomass (kg ha$^{-1}$, fresh matter) of old (OV) and modern (MV) wheat varieties in organic (ORG) and conventional (CON) trials. Mean and standard error of the mean.

| | | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|---|
| | | OV | MV | OV | MV | OV | MV |
| ORG | Grain yield | 2343a±248.8 | 1326b ± 214.9 | 2706b ± 116.6 | 4245a±212.7 | 1448a±148.8 | 1484a±162.4 |
| | Straw | 7899a±641.1 | 4970b ± 369.6 | 8709a±330.9 | 6576b ± 314.9 | 5258a±286.5 | 4053b ± 198.8 |
| | Weed | 7366a±1480.9 | 9516a±1550.9 | 6b ± 3.1 | 65a±19.1 | 137b ± 32.9 | 371a±67.8 |
| CON | Grain yield | 2590b ± 176.9 | 3560a±352.9 | 1534a±218.9 | 1506a±284.3 | 1732a±207.3 | 1538a±228.3 |
| | Straw | 18193a±1170.6 | 16805a±1168.8 | 13637a±720.7 | 8693b ± 634.1 | 11002a±755.3 | 10770a±629.9 |
| | Weed | 1114b ± 193.4 | 2443a±263.9 | 1074b ± 172.7 | 1974a±251.0 | 1153b ± 297.9 | 2911a±253.6 |

*Different letters represent significant differences between OV and MV within each growing season at a level of 0.05 (Tukey test).

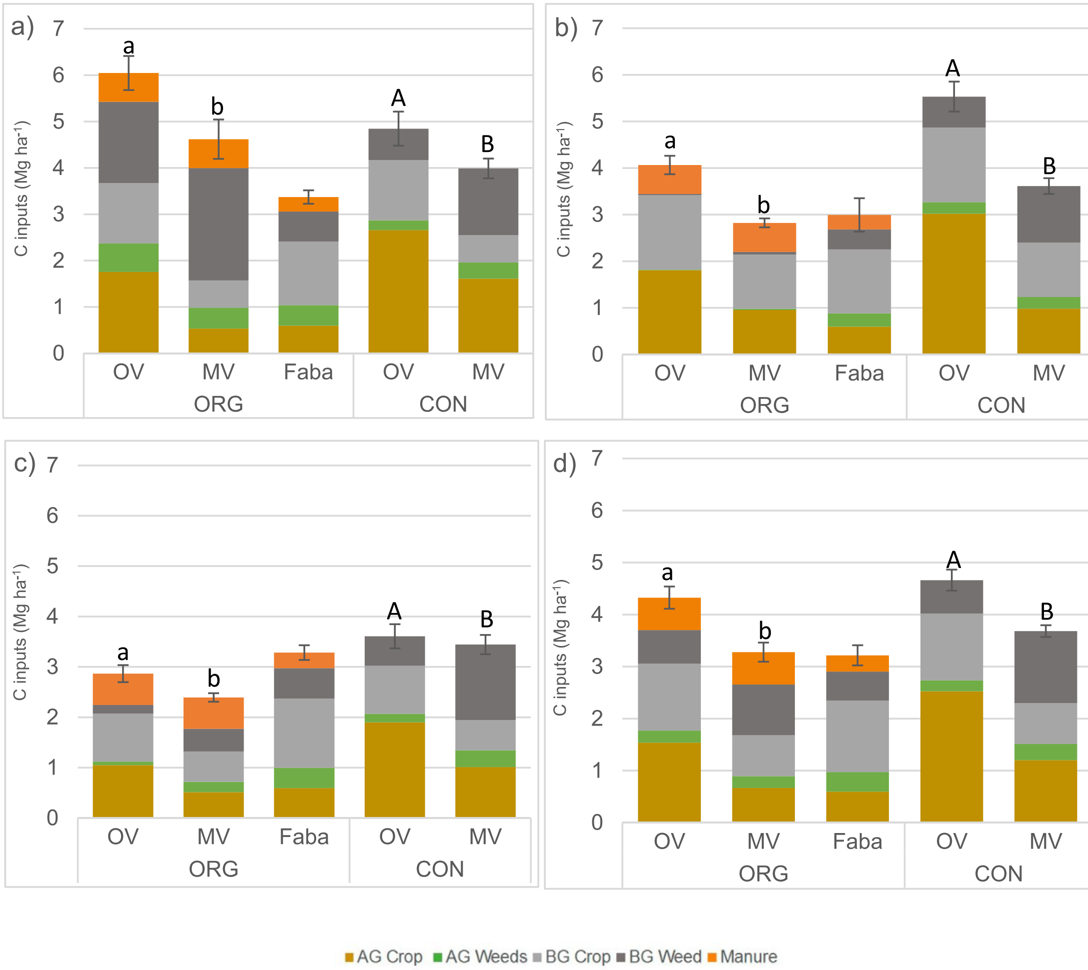


**Fig. 2.** Total carbon inputs to the soil (Mg C $ha^{-1}$) due to aboveground crop (AG crop) and weed (AG weed) residues, belowground crop (BG crop) and weed (BG weed) residues, and manure for organic (ORG) and conventional (CON) managements, in 2014 (a), 2015 (b) 2016 (c), and average values for the three growing seasons (d). OV = old variety; MV = modern variety. Different letters indicate significant differences between OV and MV for total carbon inputs (ANOVA, $p < 0.05$). Comparisons between both systems do not appear in the figure, as they may be affected by "site effect" (see Section 2.5.). Bars stand for standard error of the mean.

management, while no significant differences were found under ORG (Fig. 3d).

### 3.4. Soil organic carbon balance

Although C input of OV were higher under CON (Fig. 2d), SOC sequestration rate was higher under ORG. This was because total humified C inputs were higher under ORG due to the relatively high humification coefficient of manure. Taking into account only the cereal phase in the case of ORG, the highest simulated SOC sequestration rate (−999 kg $CO_2$ $ha^{-1}$ $y^{-1}$) was achieved with OV cultivation under ORG management (Fig. 4d, Table S9), and it was higher than values estimated for rainfed organic cereal in Aguilera et al. (2015a) and for conventional cereal in Álvaro-Fuentes et al. (2009) and Novara et al. (2016). MV under CON showed the lowest rate (−292 kg $CO_2$ $ha^{-1}$ $y^{-1}$), with similar values than those measured in a 16-year continuous barley field under reduced tillage by Álvaro-Fuentes et al. (2009), but lower than those measured in a continuous wheat cropping system by Novara et al. (2016). OV under CON management showed a relatively high C sequestration rate of −659 kg $CO_2$ $ha^{-1}$ $y^{-1}$, indicating a relevant potential of OV to increase C sequestration also under CON management, without a significant decrease in yield (Table 3). SOC increments are central for soil quality and protection against erosion, which are important factors in desertification-prone Mediterranean agroecosystems (Aguilera et al., 2013), hence OV cultivation could help to soil sustainability under Mediterranean conditions. Sequestration rate of legume was lower (2014), intermediate between OV and MV (2015) and higher (2016) than sequestration rate of wheat (Fig. 4). Accordingly, the 3-years averaged C sequestration rate of ORG taking into account the faba bean phase was lower than that exclusively for wheat (Fig. 4d), in line with experiments comparing wheat in rotation with legume with monoculture wheat (Tellez-Rio et al., 2017).

### 3.5. Nitrous oxide ($N_2O$) emissions

$N_2O$ emissions are an important source of uncertainty in agricultural GHGe balances, mainly because EFs are climatic-specific, and they show a distinct pattern in Mediterranean cropping systems (Cayuela et al., 2017). In our calculations, 3-year average $N_2O$ emissions were very similar among all of the studied wheat treatments. However, when wheat and legume emissions were averaged, the ORG rotation showed lower emissions than CON management.

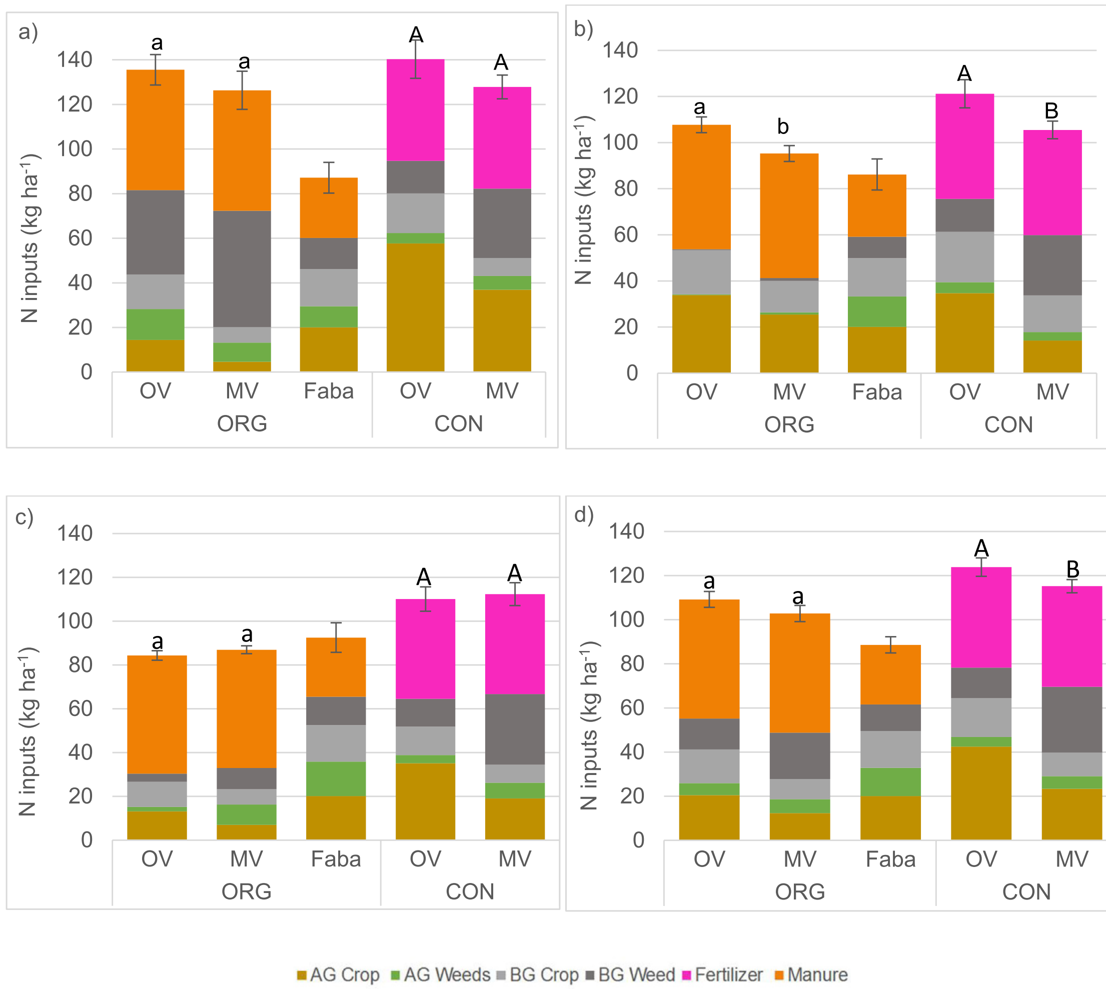


**Fig. 3.** Total nitrogen inputs to the soil (kg N $ha^{-1}$) due to aboveground crop (AG crop) and weed (AG weed) residues, belowground crop (BG crop) and weed (BG weed) residues, manure for organic (ORG) and synthetic fertilizer for conventional (CON) management, in 2014 (a), 2015 (b) 2016 (c) and average values for the three growing seasons (d). OV = old variety; MV = modern variety. Different letters indicate significant differences between OV and MV for total nitrogen inputs (ANOVA, $p < 0.05$). Comparisons between both systems do not appear in the figure, as they may be affected by "site effect" (see Section 2.5.). Bars stand for standard error of the mean.

#### 3.5.1. *Direct $N_2O$ emissions*

Direct $N_2O$ emissions represented the second largest source of GHGe in ORG, with an average of 19.0% and 17.8% for OV and MV (Fig. 4d, Table S9), respectively. For the legume phase, they represented a 17.0% of GHGe and were third in relevance, very near from 17.4% of machinery and fuel production. Under CON management, they were the third source of emissions with a share of 13.0% and 12.0% for OV and MV. Previous studies found direct $N_2O$ emissions as the greatest source of GHGe in Mediterranean wheat cropping systems (Ali et al., 2017), likely due to the use of higher EFs, higher residue N content and higher N fertilizer rates than those of this study. Relatively low direct $N_2O$ emissions estimated in this work are due to low N application rates and low $N_2O$ EFs, in line with most Mediterranean rainfed systems (Cayuela et al., 2017). Biswas et al. (2008) found low proportions of $N_2O$ emissions from direct emissions from a conventional wheat field (9%), although this share increased up to 36% of the total when applying IPCC values. This study, in agreement with Biswas et al. (2008) and Aguilera et al. (2015a), highlights that the use of specific EFs for $N_2O$ emissions estimates rather than default values is recommended for LCA under Mediterranean rainfed conditions.

Considering the legume phase, we calculated higher average emissions for the cereal than for the legume phase, due to higher N inputs from poultry. Previously, field measurements did not report an increment in $N_2O$ emissions during the legume phase in a cereal-legume rotation (Barton et al., 2013).

#### 3.5.2. *Indirect emissions*

$N_2O$ emissions from N losses through volatilization are shown in Table S5. Rainfall scarcity during the field experiment period, along with high evapotranspiration and soil texture lead to dismiss $NO_3^-$ leaching processes, following IPCC (2014). Under ORG, the contribution of indirect emissions to the overall GHGe was 5.9% and 3.2% for wheat and the legume, respectively; while proportion was only 0.4%, under CON (Fig. 4). Ali et al. (2017) found this contribution to be much higher for a Mediterranean cereal field (5%), due to the leaching losses emissions, higher fertilization rates and higher $NH_3$ volatilization proportion considered.

Crop residue management can influence the GHGe balance in opposing ways. Here, crop residues and roots incorporation increased direct $N_2O$ emissions of OV, but they also promoted C sequestration. In addition, non-incorporated residues also contribute to GHGe when they are burnt or used for animal feed or bedding (Lehtinen et al., 2014), although this has not been considered in this balance.

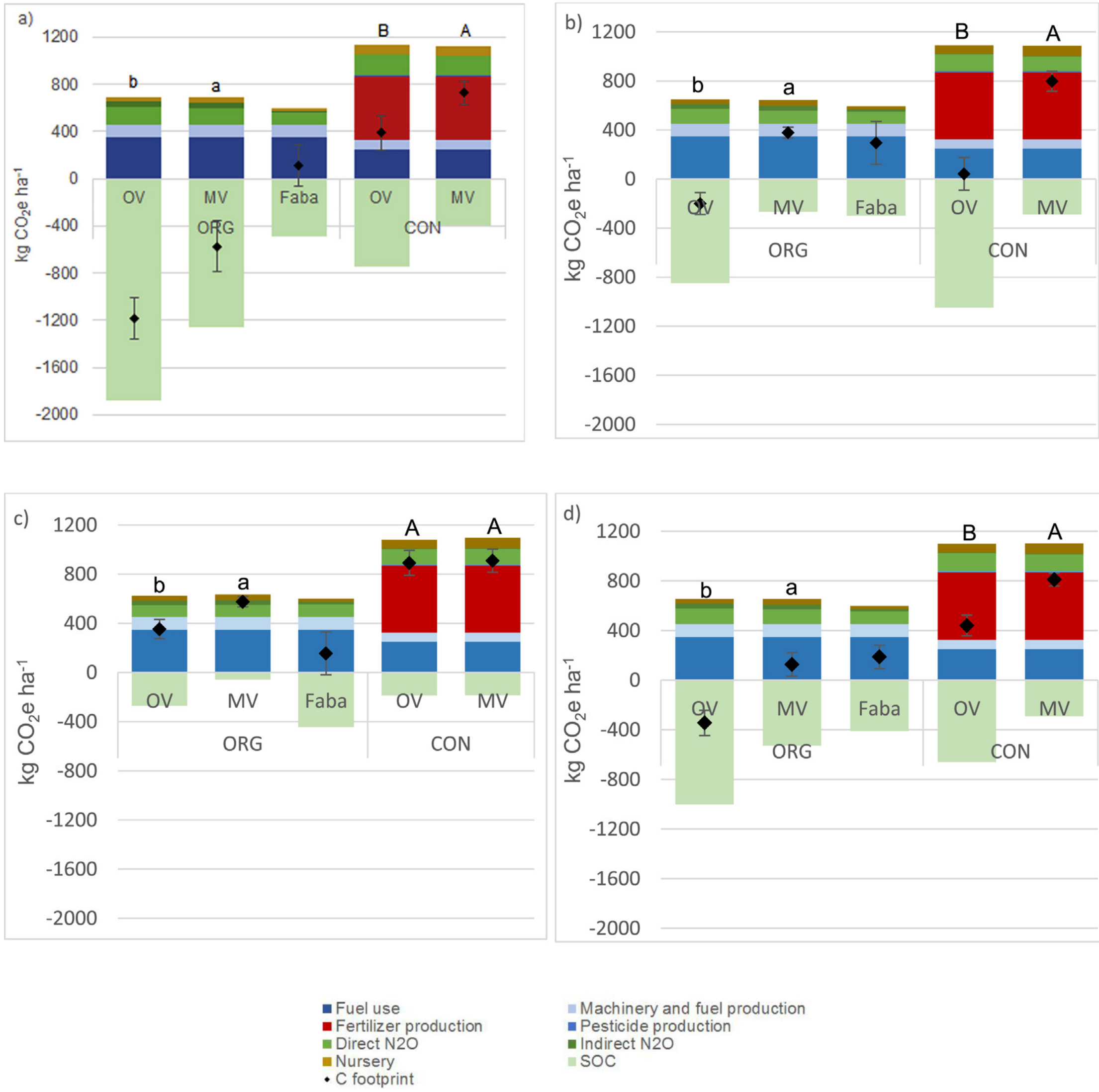


**Fig. 4.** Greenhouse gasses emissions (GHGe, kg $CO_2$e $ha^{-1}$) from soil, on-farm operations and inputs manufacturing for old (OV) and modern (MV) wheat varieties cultivation under organic (ORG) and conventional (CON) management and wheat-faba bean rotation under ORG management in 2014 (a), 2015 (b) and 2016 (c) and the average of the three years (d). Mean, and standard error (bars) area-based carbon footprint are also shown. Different letters within each location represent significant differences in the C footprint between OV and MV (ANOVA, $p < 0.05$). Comparisons between both systems do not appear in the figure, as they may be affected by "site effect" (see Section 2.5.).

### 3.6. On-farm operations and inputs production emissions

Emissions from fuel use and machinery and fuel production were higher under ORG than under CON management (Fig. 4, Table S9), contrary to other studies for Mediterranean rainfed cereal croplands (Gutiérrez et al., 2017). While this emission source only accounted for 29% and 30% of the total GHGe in the CON trial (for OV and MV), it was the major source of GHGe for ORG (69%), similar to the pattern observed by Aguilera et al. (2015a). Therefore, machinery use should be a relevant target for GHGe mitigation in organic Mediterranean rainfed systems.

Synthetic fertilizer production accounted for up to 50% of the GHGe in the conventionally managed wheat, in agreement with other conventional wheat GWP evaluations (Biswas et al., 2008). In this sense, Tuomisto et al. (2012) found that the high energy consumption and emissions associated with the production of synthetic N fertilizers were responsible for the high energy inputs of conventional farming. With a similar pattern, a recent environmental assessment of the whole process of bread manufacture in a Mediterranean region showed that the production of chemical fertilizers contribute with more than 50% to the C footprint of the cultivation phase (Ingrao et al., 2018). Pesticide production only represented 1% of GHGe, very near to the 0.5% observed for crop protection in rainfed wheat under similar Mediterranean conditions (Tahmasebi et al., 2018). The share represented by seed production was also small (6.5% and 7% for ORG and CON trial, respectively), and slightly higher than the averaged proportion of Tahmasebi et al. (2018) (2.8%).

### 3.7. Carbon footprint: area and yield-scaled GHG emissions

Highest annual area-scaled GHGe (811 kg $CO_2$e $ha^{-1}$) was found for MV under CON management, while the lowest (−345 kg $CO_2$e $ha^{-1}$) was for the cultivation of OV (without including faba bean footprint) under ORG (Fig. 4d). Across years and managements, C footprint was significantly lower for OV than for MV (Fig. 4). On average, the C footprint of faba bean was positive and higher than that of wheat in ORG (Fig. 4, Table S9), thus slightly augmenting the

C footprint of the rotation when averaging wheat and faba bean data. Our finding for organic MV C footprint was lower than that by Aguilera et al. (2015a) (361 kg $CO_2$e $ha^{-1}$), mainly due to our higher SOC sequestration rates. Likewise, our C footprint under CON is lower than those from other studies of modern cereal varieties under conventional management. For instance, Ali et al. (2017) found a higher C footprint of 1481 kg $CO_2$e $ha^{-1}$, because of their higher $N_2O$ emissions, GHGe related to inputs production and the lack of inclusion of the SOC balance.

Averaged GHGe for wheat-legume rotation in our study was lower than findings for a long-term wheat under rotation (Tellez-Rio et al., 2017), likely because, on average, their SOC contribution to the GHG balance was positive, rather than negative. This fact further highlights the relevance of the SOC balance in C footprint assessments. Comparing C footprint components, C sequestration and farm inputs and operations were more relevant than $N_2O$ fluxes, in agreement with Guardia et al. (2016) and Aguilera et al. (2015a).

Trends for the yield-scaled C footprint were similar to those of the area-scaled analysis (Fig. 5b, Table S9). Mean value for the three growing seasons of OV was significantly lower than for MV under both managements. Our data for MV under CON management, which represents conventional cereal production, agrees well with the values reported by Biswas et al. (2008) and Ali et al. (2017) for conventional wheat under Mediterranean conditions. Although not statistically comparable, a trend of lower yield-scaled C footprint under ORG management can be depicted from our results, which matches with previous findings under Mediterranean conditions (Aguilera et al., 2015a) and with previous organic and conventional European farming systems comparisons (Tuomisto et al., 2012). This lower C footprint on a product basis could lead to lower GWP of final wheat products, such as bread (Meisterling et al., 2009). Contrastingly, Chiriacò et al. (2017) found higher GHGe from an organic bread due to the lower yields compared to conventional whole meal bread, and Tricase et al. (2018) observed a higher environmental impact of organic barley on a product basis when compared to conventional barley. Tahmasebi et al. (2018) found a correlation between yield and GHG emissions for rainfed wheat, but also lower product C footprints for higher wheat yields. Our results do not follow this relation, as higher C footprint was estimated for MV while such trend was not always true for yield. This difference can be due to the inclusion in our study of the soil C balance in the emission assessment and the higher C inputs for OV.

The higher aboveground and belowground residue production of OV led to a large C sequestration rate, responsible for a lower C footprint for OV. SOC balance contribution to C footprint reduction ranged from −146% in OV-ORG plots to −25% in MV-CON plots. C sequestration of OV in the ORG trial offsets all other GHGe, while this was not true for MV. Our results strengthen the hypothesis that SOC balance is a major contributor to the variation of the C footprint of agricultural products (Gan et al., 2014), so it is important to account for it in GHGe balances (Rodríguez-Entrena et al., 2014). In Mediterranean agroecosystems, where soil C shows great responses to organic inputs (Aguilera et al., 2015a) and contribution to $N_2O$ emissions is low (Guardia et al., 2016), C sequestration as an option to climate change mitigation should be fostered (Tellez-Rio et al., 2017). It is worth noting that SOC changes are highly dependent on specific site pedo-climatic conditions and agronomic practices (Francaviglia et al., 2017), and variation between C footprints estimates should warn us about the relevance of more detailed and local studies to determine specific site and cropping conditions and management-related mitigation strategies.

As happened with area-scaled C footprint, the legume phase harbored higher C footprint than the wheat phase. Thus the C footprint of the rotation scheme was higher than that of wheat, contrary to the findings of Gan et al. (2014) for wheat grown after a legume instead of a cereal. In the legume phase of the rotation, the contribution of SOC accumulation to the reduction in the C footprint averaged −60%.

Crop residues incorporation to soils can have several advantages to mitigate climate change impacts in dry and hot environments (Liu et al., 2017). Provided that an adequate quantity of the additional residue production of OV is returned to the soil, our results show that it can benefit the sustainability of rainfed cereal production under Mediterranean climate, particularly under organic management, where their cultivation resulted in a negative C footprint.

These results could potentially be applicable in other semiarid systems beyond the Mediterranean climate. In any case, further field investigation is needed to confirm our conclusions and ensure that both systems could benefit from the results of the present study. In addition, introducing a legume in rotation with cereal has

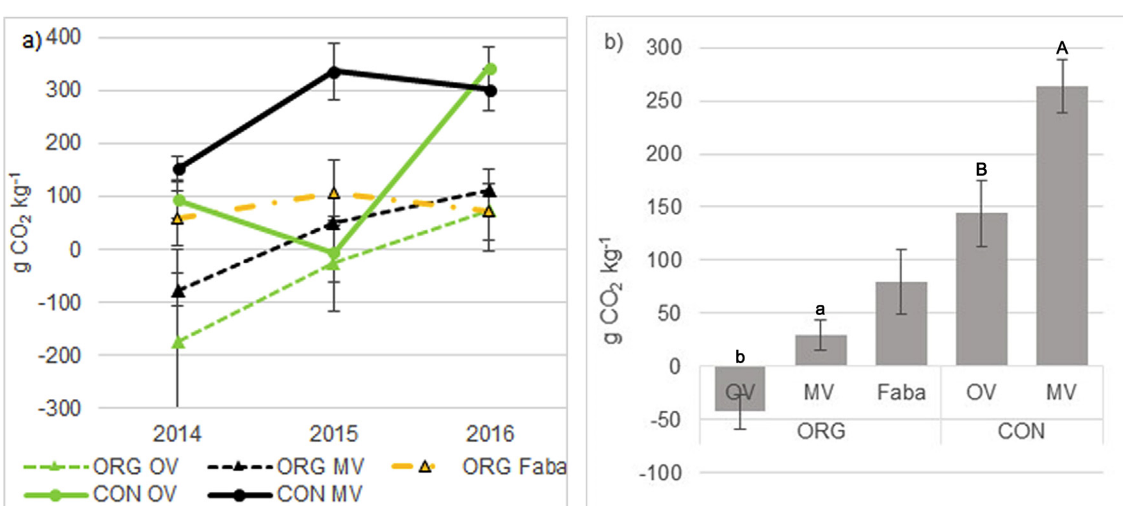


**Fig. 5.** Yield-scaled C footprint (GHGe, g $CO_2$e kg $grain^{-1}$) for old (OV) and modern (MV) wheat varieties, and faba bean, under organic (ORG) and conventional (CON) management for the three growing seasons (a), and for the 3-year average (b). Different letters within each location represent significant differences in the C footprint between OV and MV (ANOVA, $p < 0.05$). Comparisons between both systems do not appear in the figure, as they may be affected by "site effect" (see Section 2.5.). Error bars stand for standard error of the mean.

several advantages, such as weed control (Díaz-Ambrona and Mínguez, 2001) or as a valuable protein source (Christiansen et al., 2015). The advantages of organic cereal-legume rotations could be boosted by introducing genetic material better suited to organic farming, like old wheat cultivars in comparison to modern breeding cultivars, as has been shown in this study.

A higher level of specificity and regionalized data are needed to provide more valuable and deeper LCA analyses of food production systems (Notarnicola et al., 2017). Policy makers searching for options to face the climate change challenge could find new insights if adopting a regional approach. In addition, strategies may be developed through the collaboration of farmers and researchers in order to better identify the potential constraints to their expansion. In this respect, we have supported our LCA with field experiment data as well as with specific Mediterranean emission factors and SOC modeling, strengthening the validity and applicability of the results. This has allowed us to observe that SOC sequestration, the on-farm use of fuel and machinery and the application of chemical fertilizers should be taken as key aspects for the development of climate change mitigation strategies in Mediterranean rainfed systems.

## 4. Conclusions

The results of this study show relevant differences in the carbon footprint of old and modern wheat varieties under organic and conventional rainfed Mediterranean conditions. Fertilizers production, in conventional systems, and machinery use, in organic systems, were identified as the major GHGe hotspots of wheat cultivation, indicating the need for mitigation efforts. Carbon sequestration was also an important component of the GHGe balance, and it was responsible for the significant reduction in the C footprint observed with old varieties, due to the higher straw and root biomass. Old varieties also suffered of a lower weed infestation than modern ones, whereas grain yield was not significantly reduced. Overall, higher biomass incorporation to the soil with old varieties was responsible of higher negative values for C balance and higher $N_2O$ emissions, but the former broadly offset the latter, resulting in a lower C footprint both area and yield-scaled, and even in a negative C footprint for old varieties under ORG. Therefore, the results stress the relevance of C sequestration in climate change mitigation and the importance of including it in C footprint accountings. In conclusion, old varieties have shown a large potential for enhancing C sequestration and reducing the C footprint through high residue production, which makes them particularly promising for climate change mitigation in organic and low input systems.

## Conflicts of interest

None.

## Acknowledgements

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.05.188.

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